

Augmented Reality: Reflections at Thirty Years

Louis B. Rosenberg

Abstract. Three decades ago in a small lab at Wright Patterson Air Force Base, the first functional augmented reality (AR) system was formally tested on groups of human subjects, each of them experiencing for the first time, interactive virtual objects that were seamlessly merged into their perception of the real world. The system, known as the *Virtual Fixtures* platform, produced virtual overlays that felt physically real and were spatially registered with such 3D precision, they could be used to significantly boost human performance in dexterous real-world tasks. Now three decades later, the principal investigator of that early effort reflects on the lessons learned, the unexpected delays in achieving widespread adoption of AR, and future prospects and dangers as the field goes mainstream.

Keywords: Augmented Reality, Virtual Reality, Mixed Reality, XR, VR, AR

1 Augmented Reality – Early Days

Thirty years ago this winter, a project kicked off that would produce the first functional augmented reality (AR) system enabling interactive virtual objects to be spatially registered to a user's perception of the real world in an authentic and meaningful way. The goal was to empower users to physically interact with real and virtual objects as a single unified reality. Known as the *Virtual Fixtures* project, the effort was funded by Air Force Research Laboratory (AFRL) with additional support from the Stanford University, Center for Design Research (CDR) and the NASA virtual reality lab, known then as the Advanced Displays and Spatial Perception Laboratory. The objective was to simulate virtual objects and overlay them onto our perception of the real physical world in a seamless manner that would look, sound, and feel so believable, the virtual entities would be perceived by users as authentic additions to real environments [1]. In fact, the intent was to create and test a mixed reality experience that was so convincing, it could significantly enhance human performance in real-world tasks.

As the principal investigator on the Virtual Fixtures effort during the early 1990s, I can't help but reflect on the promise of Augmented Reality as it was contemplated back then as compared to now. It's not merely the 30 year anniversary that makes a look backwards fitting, but the fact that the world is finally getting close to deploying immersive AR / MR on a consumer scale. Last year, Apple CEO Tim Cook discussed the topic openly for the first time, confirming that the company was investing heavily

in an AR enabled future, calling the technology “the next big thing” and predicting “it will pervade our entire lives” [2]. In the months since, it has been widely reported that Apple plans to release the first of multiple AR headsets in 2022, having assembled the largest internal team since the iPhone development effort [3]. And it’s not just Apple pushing forcefully into AR – both Google and Facebook have been investing heavily, aiming for major products in the near future. With such an aggressive surge of activity, it seems very likely that the 2020’s will be the decade of Augmented Reality.

Of course, those of us involved from the early days believed the 1990’s would be the decade of AR, as well as the 2000’s and 2010’s. That said, this time feels different. In fact, for the first time the prospects for widespread adoption of AR have eclipsed traditional VR in the minds of most analysts as markets finally realize the profound benefit of being able to interact with virtual content seamlessly overlaid onto the real world [4]. And of course, the critical element that makes AR different from old school heads-up displays is accurate spatial registration [5] – enabling virtual objects and physical objects to be correlated with enough precision that they become part of a single perceptual reality. It’s the spatial registration problem that’s finally being tackled at low cost and may, at long last, enable AR to become a mainstream technology.

Having pondered commercial applications of AR for thirty years, I am eager to see its magical potential finally realized. At the same time, I am increasingly worried there could be a dark and damaging side. I say that because the impact of technology is so different today than it was back when AR was first conceived. The unfortunate fact is, interactive media has taken a turn for the worst in recent years, being abused in ways that few could have imagined back then. From the widespread manipulation of public opinion using AI-driven misinformation, to the rise of deep-fakes, chat-bots, and troll-farms, interactive media now make us question the boundaries between fact and fiction. Before delving into my specific concerns for how AR may amplify these emerging societal dangers, let’s jump back to those innocent early days of AR and reflect upon the development of that first interactive system and the insights the research revealed.

1.1 The Virtual Fixtures Project

The development effort began in 1990 at Stanford University, years before phrases like Augmented Reality (AR), Extended Reality (XR), or Mixed Reality (MR) had been coined. The objective was to explore whether real and virtual worlds could be merged into a single “ambient reality” that was sufficiently realistic to induce suspension of disbelief, enabling users to feel *physically present* in a unified immersive environment that seamlessly combined real and virtual objects. The virtual objects that were simulated and overlaid onto the real world were designed to amplify human performance in physical tasks, enhancing speed and dexterity in much the same way that real-world fixtures do. For this reason, the effort was called the Virtual Fixtures project as it involved simulating fixtures and projecting them into real environments.

The initial concept was developed at the Stanford Center for Design Research (CDR) founded by Prof. Larry Leifer and funded by Hewlett Packard, Apple Computer, and BMW [19]. At the time, researchers affiliated with CDR were developing core VR technologies, including some of the first VR gloves created by James Kramer [6,7], some of the early 3D audio systems developed by William Chapin [8], and some of the first VR displays created by Mark Bolas [9, 10]. Because commercial technology did not exist to combine real and virtual environments with precise spatial registration, significant resources would be required to develop and test the Virtual Fixtures concept. To secure such resources, viable use-cases had to be developed that could be pitched to potential sources of funding and equipment. From education and entertainment to tele-robotics and scientific visualization, many viable concepts were explored.

Of the many proposed application areas, one that generated significant excitement was the use of Virtual Fixtures in the field of medicine. In particular, the concept of “augmented surgery” was developed [1], which generated substantial interest from the U.S. Air Force. As shown in Fig. 1 below, the idea was to overlay virtual fixtures onto real-world patients that assist medical professionals during dexterous procedures.

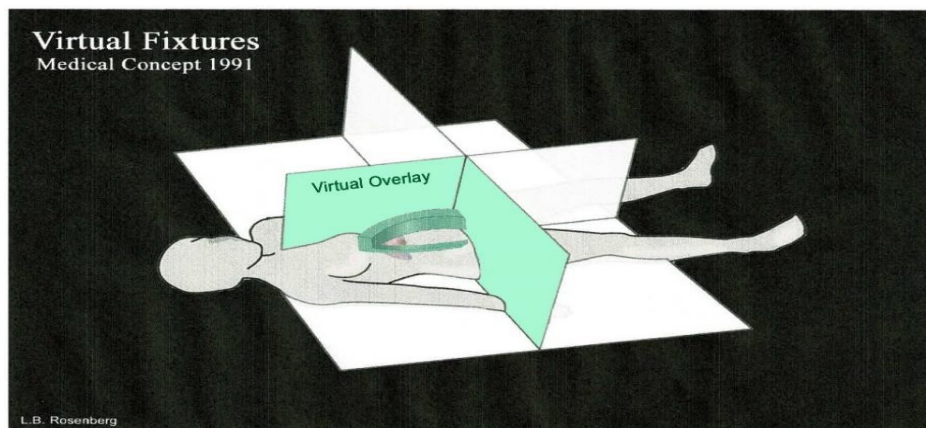


Fig. 1. Virtual Fixtures interface, Medical Concept - 1991

To convey the value of Virtual Fixtures during surgery, a physical analogy was used to explain the concept – line drawing. Simply put, if you challenge an individual to draw the straightest line they can, they will move their pencil slowly and carefully, expending significant mental and physical effort. But if you give that same person a simple assistive fixture, for example a standard ruler or straight edge, they can draw the same line faster, easier and straighter, while consuming significantly less mental and physical effort. Clearly, the use of fixtures can greatly enhance human performance.

Now imagine that instead of a ruler guiding a pencil, more complex fixtures were used to guide the surgeon's scalpel along a specific trajectory or to protect vital organs. Like a simple ruler, such a fixture could enhance performance, increasing speed while reducing mental and physical effort. Of course, the ideal fixture would not simply rest on the surface of the body but would pass through the tissue of the patient, guiding the scalpel in regions that are not yet surgically exposed. To achieve such an ideal fixture, why not create it virtually? Hence the proposal to generate Virtual Fixtures in 3D space, not just visually but physically, emulating the look, feel, and sound of a real scalpel interacting with virtual guides. In other words, create an augmented reality experience in which a skilled surgeon could interact simultaneously with a real patient and virtual overlays, the goal to significantly enhance human performance.

Based on the proposed applications in medicine, tele-robotics and education, Air Force Research Laboratories backed the Virtual Fixtures project, providing access to equipment and resources at Wright Patterson Air Force Base. The goal was to demonstrate that (a) a real workspace could be convincingly augmented with virtual objects and (b) that the resulting mixed reality could enhance human performance in real-world tasks. To assess potential across a wide range of applications, a standardized task was chosen to quantify human performance in a generalizable way. Known as a *Fitts's Law Peg Insertion Task* [11], the protocol required human subjects to move metal pegs between holes as quickly as they could. By varying the distance between the holes and the *fit tolerance* of the pegs (i.e. size difference between peg and hole), a rigorous Index of Performance (IP) could be calculated for each trial using well known methods. A standard Fitts's Law task board was used study as shown in Figure 2 below.



Fig. 2. Fitts's Law Peg Insertion Task Board

Having defined the task, the next step was to design a system that could overlay interactive virtual objects upon a user's perception of a physical workspace and do so with sufficient realism and registration that they would be perceived as authentic additions. The system employed a wide range of experimental hardware, including an upper-body exoskeleton that could accurately track body kinematics, monitoring a user's hand-motion from the base of their torso to the center of their palm. The exoskeleton took a variety of forms over the multi-year effort, but ultimately used a high fidelity force-reflecting structure with large brushless motors that could be programed to physically simulate a wide range of virtual objects from simple surfaces to complex contours. The exoskeleton was strong enough to generate forces that a user could not easily overpower. This enabled the creation of interactive virtual overlays that were (a) perceived as physically genuine and (b) were accurately registered in three-dimensional space to the real-world aspects of the physical task.

Figure 3 below is a simple schematic of the Virtual Fixtures system circa 1992. As shown, the human subject wore an upper-body exoskeleton while peering into a vision system and listening to audio. The participants were tasked with moving metal pegs as quickly as they could between a series of holes, following a sequence of trials that tested a variety of difficulties. The regimen included direct manipulation of the pegs as well as manipulation of the pegs through a robotic interface, which allowed for the testing of telepresence scenarios that introduced additional complexities like time delay. A photograph of the test setup from 1992 is shown in Figure 4.

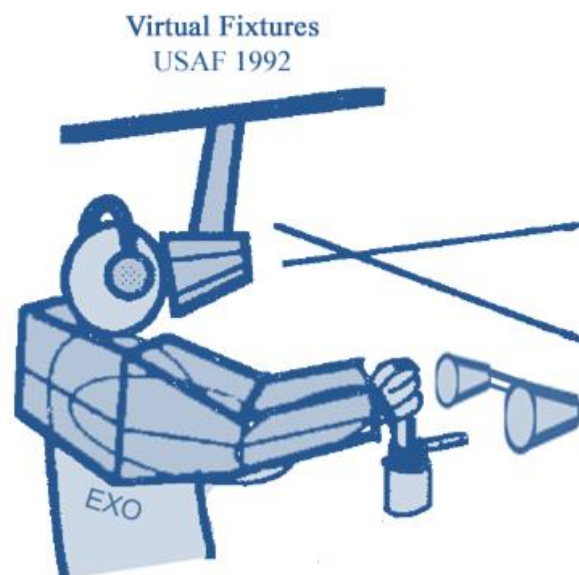


Fig. 3. Early schematic of Virtual Fixtures system

A variety of virtual fixtures were simulated and tested on human subjects, from simple flat surfaces to complex 3D profiles, including rigid barriers, compliant surfaces, textured surfaces and viscous liquids. Some of the simulated fixtures also included a 3D audio component in which sounds were modulated with peg motion in 3D space. One particularly promising set of fixtures was programmed to create physically realistic cones that were spatially registered to the task-board such that if a user pushed a real peg into the virtual cone, the fixture would help guide the peg into the real hole.

Another type of virtual fixture that was highly effective were called “snap-to” surfaces, as they were rigid surfaces that were simulated to have magnetic attraction, enabling the user to snap the peg to the virtual surface and then, by overpowering the simulated force, un-snap and move freely. These fixtures were tested to explore an important aspect of augmented reality – namely the ability to project simulated objects into the real world that are convincingly authentic (i.e. *feel real*) but that have properties that could not be easily created in the real world using traditional materials.

Ultimately, a diverse cohort of human subjects were run through a variety of testing regimens, each performing sequences of trials in which they rapidly transferred pegs between target holes of varying distances and varying tolerance. They performed these tasks first without the use of virtual overlays, capturing baseline performance, and then with the support of virtual augmentation across a variety of fixture designs. Trials were also run to test the value of Virtual Fixtures in telepresence scenarios in which the operator inserted the peg by controlling a remote robot with simulated time-delay of 250 and 450 milliseconds. These delays were used to emulate the real-time control of repair robots in various earth orbits from a ground station.



Fig. 4. Principal Investigator (Louis Rosenberg) Testing Virtual Fixtures System

Ultimately, the Virtual Fixtures project produced a set of encouraging results. As first published in 1992, the initial study demonstrated that simple virtual fixtures comprised of rigid surfaces could enhance performance significantly [1,12]. A set of eight virtual fixtures were tested on the standard Fitts's Law Peg Insertion task achieving performance increases up to 70% as compared to without augmentation. As published in 1993 and 1994, additional studies were performed on more elaborate virtual overlays, expanding beyond rigid surfaces to simulated compliant surfaces, simulated magnetic surfaces, simulated textured surfaces, and simulated viscous liquids. An example of a cone-based fixture is shown below in figure 5. In this round of studies, human performance was amplified by over 100%, more than doubling the speed of task performance while reducing mental workload [13-15].

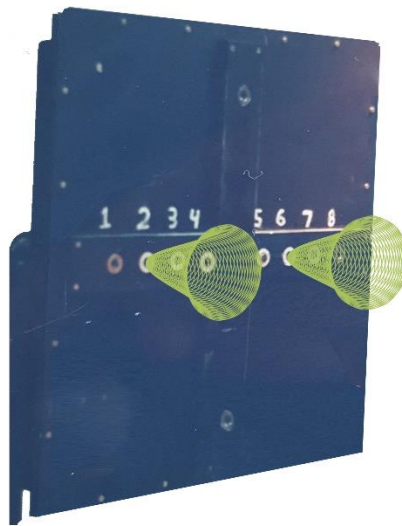


Fig. 5. Virtual Fixtures were registered to the real-world task board. The fixtures depicted here are 3D cones that physically guide the user.

In addition, a follow-up study conducted in the virtual reality lab at NASA Ames Research Center tested if human subjects could design their own virtual fixtures to aid their performance in a given real-world task. Known as the “Perceptual Workstation,” software was created in which participants could use a graphical interface to design Virtual Fixtures from a set of primitives including (a) rigid surfaces, (b) viscous liquids, (c) virtual bumps, (d) repulsive fields, and (e) spatial textures [15]. Because of technical limitations in the early 1990’s, this set of tests was limited to two-dimensional fixtures for use in a two-dimensional task. Still, the results showed that human participants could quickly design their own virtual fixtures that enhanced their own performance. In fact, mean performance increase of 109% was recorded across a wide range of subjects, each of whom created unique fixture strategies to augment the task [15-17].

In addition to capturing rigorous performance metrics, post-testing interviews were conducted with participants (both active duty Air Force personnel and civilians) in which they reflected upon their experience using the technology. Without exception, the subjects reported that the virtual overlays were well integrated into their perception of the physical world, giving them the strong impression that the fixtures were authentic additions to the workspace. The fixtures were perceived as so real in fact, many subjects reported having increased confidence during the task. Subjects were then asked to volunteer additional thoughts. Without exception, the subjects reported being surprised by how realistic the virtual content seemed during interactions. Unprompted, many participants predicted that this style of real/virtual experience (now called Augmented Reality) would quickly take off and ultimately become part of mainstream computing.

Needless to say, the proliferation of AR technology didn't happen as quickly as I expected. In those years, the primary barriers were cost and size. The system used to conduct the Virtual Fixtures project cost hundreds of thousands of dollars and was anything but compact. The vision system (optics and cameras) had to be mounted on the ceiling to support weight and the exoskeleton was a massive device. Still, I was convinced that both AR and VR would become mainstream technologies by the end of the 1990's. Clearly, I was off by a few decades. That said, the 2020's may finally realize the potential of AR, unleashing consumer products that finally enable real and virtual worlds to be combined with sufficient realism and 3D registration to induce genuine suspension of disbelief.

2 The Future of AR

Although it took decades longer than many people expected, consumer markets may finally be on the verge of deploying augmented reality (mixed reality) on a global scale. Last year Gartner Research declared that AR had matured past the "Hype Cycle" stage and was rapidly becoming a mature technology [18]. In fact, many industry analysts now expect AR to impact the lives of most Americans within the next 5 years, affecting how we work, play, learn, shop and socialize. Magical applications are surely on the way that will enrich our lives, splashing the power and flexibility of immersive computing onto the whole world around us. And yet, I am increasingly concerned about the potential negative ramifications of augmenting the physical world with virtual objects that look, sound, and feel convincingly real.

At its core augmented reality is a media technology, presenting content in the most natural form possible – seamlessly integrated into our perception of the world around us. This means AR, more than any form of media to date, has the potential to impact our sense of what's real, altering how we interpret our experiences and interactions. In an augmented world, simply walking down the street will become an amalgamation of the real and the unreal, merged so convincingly that the boundaries will disappear in our minds. Our surroundings will be filled with persons, places and activities that don't actually exist and yet they will seem as authentic to us as any other part of the physical world. This is both exciting and terrifying.

When I first considered the power of AR in the early 1990's, I wasn't particularly concerned that bad actors would misuse the technology. Now thirty years later, I'm very concerned, but it's not because of what criminals might do. It's because we find ourselves in a society where countless layers of technology exist between each of us and our daily lives, moderating our access to news and information, mediating our relationships with friends and family, filtering our impressions of products and services, even influencing our acceptance of basic facts. We now live *mediated lives*, all of us depending more and more on the corporations that provide and maintain the intervening layers. And when those layers are used to manipulate us, we don't view it as "misuse," but "marketing." And it's not just being used to peddle products, but to disseminate misinformation and promote social division. The fact is, we now live in dangerous times and AR has the potential to amplify the dangers to levels we've never before seen.

Imagine walking down the street in your hometown, casually glancing at people you pass on the sidewalk. It's much like today, except floating over the heads of every person you see are big glowing bubbles of information. Now imagine that third-parties can inject divisive content, like trolls on Facebook – but now it's bold flashing words over certain people that say "Alcoholic" or "Immigrant" or "Atheist." Those who are tagged may not even know that's how others see them. The virtual overlays could easily be designed to amplify political division, oppress certain groups, even drive hatred and mistrust. Will this really make the world a better place? Or will it take the polarized and confrontational culture that's emerged online and splash it all over the real world?

Now imagine you work behind a retail counter. Augmented Reality will change how you size up your customers. That's because personal data will float all around them, showing you their tastes and interests, their spending habits, the type of car they drive, the size of their house, even their gross annual income. It would have been unthinkable decades ago to imagine corporations having access to such information, but these days we accept it as the price of doing business in a digital world. With AR, personal information will follow us everywhere, exposing our behaviors and reducing our privacy. Will this make the world a better place? I don't think so, and yet this is where we're headed if current trends in data collection and personal tracking are combined with the power and flexibility of AR technology.

Over the last decade, the abuse of media technologies has made us all vulnerable to distortions and misinformation, from fake-news and deep-fakes to botnets and troll farms. These dangers are insidious, but at least we can turn off our phones or step away from our screens and have authentic real-world experiences that are not filtered through corporate databases or manipulated by intelligent algorithms. With the proliferation of AR, this last bastion of *reliable reality* will disappear. And when that happens, it will only exacerbate the social divisions that have plagued society in recent years.

After all, the shared experience we call "civilized society" is quickly eroding, largely because we each live in our own data-bubble, everyone being fed custom news and information tailored to their personal beliefs, reinforcing their biases and entrenching their opinions. But today we can at least enter a public space and have some level of shared experience in a common reality. With AR, that too may be lost. When you walk

down a street in an augmented world, you could see a city filled with content that reinforces your personal views, deceiving you into believing that everyone thinks the way you do. And when I walk down that same street, I could see vastly different content, promoting inverse views that make me believe opposite things about the very same citizens of the very same town.

Consider the tragic burden of homelessness. There will be people who choose not to see this problem for political reasons, their AR headsets generating virtual blinders, hiding soup kitchens and homeless shelters behind virtual walls, much like construction sites are hidden in today's world. There will be others who choose not to see fertility clinics or police protests or whatever else the prevailing political forces encourage them to "*reality block*." At the same time, consider the impact on the poorest members of society. If a family can't afford AR hardware, they will live in a world where critical content is completely invisible to them – talk about disenfranchisement.

And no, you won't just take off your AR glasses or pop out your contacts to avoid these problems. Why? Because faster than any of us can imagine, we will become thoroughly dependent on the virtual layers of information projected all around us. It will feel no more *optional* than internet access feels optional today. You won't unplug your AR system because doing so will make important aspects of life invisible to you, putting you at a disadvantage socially, economically and intellectually. The fact is, the technologies we adopt in the name of convenience rarely remain optional – not when they're integrated into our lives as broadly as Augmented Reality will be.

So yes, thirty years in – I am worried. And it's not because I don't still believe in the potential of Augmented Reality to enrich our lives in wonderful ways. I remain confident that AR will enable surgeons to perform faster and better, construction workers too, engineers and scientists – everybody, young and old. I am also confident that AR will revolutionize entertainment and education, unleashing experiences that aren't just engaging and informative, but thrilling and inspiring. There will be countless positive applications – bringing people together and reducing social division. Simply put, AR has the potential to make the world a magical place.

But AR will also make us even more dependent on the layers of technology that mediate our lives and the companies that control those layers. This will leave us increasingly susceptible to manipulations and distortions by bad actors. AR could be used to fracture society, pushing us from our own information bubbles to our own custom realities, further entrenching our views and cementing our divisions.

Being an optimist I still believe that AR will be a force for good, expanding what it means to be human. But to protect against such dangers, we need to proceed carefully and thoughtfully, anticipating the problems that could corrupt what should be a magical technology. If we've learned anything from the unexpected evils of social media, it is that good intentions are not enough to protect against serious problems. And once problems emerge, it's extremely difficult to undo the damage. This means the proponents of AR need to be vigilant now, thinking ahead about how we release these amazing capabilities into society and doing our best to get it right the first time.

References

1. Rosenberg, Louis. "The Use of Virtual Fixtures as Perceptual Overlays to Enhance Operator Performance," United States Air Force Technical Report ADA292450, (September 1992); 52 pages. Approved for Public Release.
2. Burke, Elaine. "Tim Cook, AR will pervade our entire lives". Silicon Republic, Jan 2020.
3. Gurman, Mark, "Apple's Secretive AR and VR Headset Plans Altered by Internal Differences". Bloomberg News, 2020-06-19
4. Augmented Reality and Virtual Reality Market by Technology and Geography - Forecast and Analysis 2021-2025, TechNavio 2021. 1-120.
5. Maida, James; Bowen, Charles; Montpool, Andrew; Pace, John. Dynamic registration correction in augmented-reality systems, archived 18 May 2013, Space Life Sciences, NASA.
6. Kramer, James. and Leifer, Larry "The Talking Glove: An expressive and receptive 'Verbal' communication aid for the deaf, deaf-blind, and non-vocal," Technical Report, Stanford University, Dept. of Electrical Engineering, Stanford, CA, 1989.
7. W. Chapin, J. Kramer, C. Haas, L. Leifer and E. Macken, "TeleSign: a sign language telecommunication system," Proceedings of Johns Hopkins National Search for Computing Applications to Assist Persons with Disabilities, Laurel, MD, USA, 1992, pp. 2-4,
8. Chapin, William and Foster, Scott "Virtual environment display for a 3D audio room simulation", Proc. SPIE 1669, Stereoscopic Displays and Applications III, (30 June 1992); <https://doi.org/10.1117/12.60436>
9. Ian E. McDowall, Mark T. Bolas, Steven D. Pieper, Scott S. Fisher, and Jim Humphries "Implementation and integration of a counterbalanced CRT-based stereoscopic display for interactive viewpoint control in virtual-environment applications", Proc. SPIE 1256, Stereoscopic Displays and Applications, (1 September 1990); doi: 10.1117/12.19898
10. Bolas, Mark. "Human factors in the design of an immersive display," IEEE Computer Graphics and Applications, vol. 14, no. 1, pp. 55-59, Jan. 1994, doi: 10.1109/38.250920.
11. MacKenzie, I. Scott (1992). "Fitts's law as a research and design tool in human-computer interaction". *Human-Computer Interaction*. 7: 91-139.
12. Rosenberg, Louis. "Virtual Fixtures" Proceedings of IEEE Virtual Reality Annual International Symposium, Seattle, WA, USA, 1993, pp. 76-82.
13. Rosenberg, Louis. "Virtual fixtures as tools to enhance operator performance in telepresence environments", Proc. SPIE 2057, Telemanipulator Technology and Space Telerobotics, (Dec 1993); doi: 10.1117/12.164901
14. Rosenberg, Louis and Adelstein, Bernard. "Perceptual decomposition of virtual haptic surfaces," Proceedings of 1993 IEEE Research Properties in Virtual Reality Symposium, San Jose, CA, USA, 1993, pp. 46-53, doi: 10.1109/VRAIS.1993.378264.
15. Rosenberg, Louis. "Virtual fixtures," Ph.D. Thesis, Dept. of Mechanical Engineering, Stanford University (1994)
16. "Force Feedback Joystick," NASA Technology Transfer Program, 1997. <https://spinoff.nasa.gov/spinoff1997/ch5.html>
17. Rosenberg, Louis. 1994. Design of a virtual rigid surface: haptic/audio registration. Conference on Human Factors in Computing Systems (CHI '94). Association for Computing Machinery, NY, NY, USA, 257-258. DOI: 10.1145/259963.260473
18. "Gartner Says 100 Million Consumers Will Shop in Augmented Reality Online and In-Store by 2020" – April 1, 2019. <https://www.gartner.com/en/newsroom/press-releases/2019-04-01-gartner-says-100-million-consumers-will-shop-in-augme>
19. https://en.wikipedia.org/wiki/Stanford_Center_for_Design_Research